# HIGH-EFFICIENCY HELICAL TRAVELING-WAVE TUBE WITH DYNAMIC VELOCITY TAPER AND ADVANCED MULTISTAGE DEPRESSED COLLECTOR

by

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ABSTRACT

A NASA-sponsored research and development contract has been established with the Watkins-Johnson Company to fabricate high-efficiency 20-watt helical traveling wave tubes (TWT's) operating at 8.4 to 8.43 GHz. The TWT's employ dynamic velocity tapers (DVT's) and advanced multistage depressed collectors (MDC's) having electrodes with low secondary electron emission characteristics. The TWT designs include two different DVT's; one for maximum efficiency and the other for minimum distortion and phase shift. The MDC designs include electrodes of untreated and ion-textured graphite as well as copper which has been treated for secondary electron emission suppression. Objectives of the program include achieving at least 55 percent overall efficiency. Tests with the first TWT's (with undepressed collectors) indicate good agreement between predicted and measured RF efficiencies with as high as 30 percent improvement in RF efficiency over conventional helix designs.

## INTRODUCTION

Improving the overall efficiency and signal quality of microwave amplifier traveling-wave tubes (TWT's) is an ongoing effort at the NASA Lewis Research Center. To further these objectives, a research and development contract has been established with the Watkins-Johnson Company of Palo Alto, California to develop a space-qualifiable, high-efficiency helical 20-watt TWT operating at 8.4 to 8.43 GHz with at least 55 percent efficiency and having excellent signal quality. This frequency was selected because it is used for the Deep Space Network, a NASA unique application that requires the utmost in efficiency. The TWT's under development will incorporate two advanced technologies; the dynamic velocity taper (DVT) (ref. 1) and the multistage depressed collector (MDC) having electrode surfaces with low secondary electron emission characteristics. Two different DVT's, the designs of which have been provided by NASA Lewis, are to be used in the program, with one designed for maximum efficiency (tube A) and the other designed to provide for minimum signal distortion and phase shift while tolerating some sacrifice in efficiency (Type B). Each DVT is characterized by a continuous reduction in helix pitch from its nominal value inthe output section of the TWT to the end of the helix. The input end of Helix Type A was designed for optimum gain by small-signal theory while the input end of helix Type B was designed by small-signal theory for small phase lag. Both helix circuits have the same overall length and share the same tube parts except for the MDC and the spent-beam refocusing sections. The spent electron beams produced by the Type A and B DVT's are sufficiently different that an MDC was specifically designed for each. The electrical designs for the MDC's were also provided by NASA Lewis. Both TWT designs incorporate spent beam refocusing sections (ref. 2) as well as low secondary electron emission electrode surfaces. Three dimensionally-identical four-stage MDC's will be fabricated for each of the two TWT designs. One each of these MDC's will have machined (but otherwise untreated) electrodes of high-purity isotropic graphite (ref.3), another will have ion-textured graphite electrodes (ref. 3), and the third will have electrodes of high-purity copper specially-treated to suppress secondary electron emission. The ion-texturing and copper treatment procedures will be performed at NASA Lewis. TWT's incorporating preliminary versions of the two DVT types described have been fabricated by the Watkins-Johnson Company and tested with the spent electron beam collected in a single-stage undepressed collector. The results of these tests indicate very good agreement between predicted and experimentally-measured RF efficiencies and improvement by as much as 30 percent over conventional circuits.

## TWT DESIGNS FEATURES

The Watkins-Johnson WJ-3618 TWT, a 40-watt space-qualified helix communications TWT operating over selected frequency ranges including 7.2 to 8.4 GHz, was selected to modify to the requirements of this program. The modified 20-watt TWT, designated now as the WJ-3716 TWT, incorporates DVT's designed to maximize RF efficiency (Type A) and produce minimum distortion and phase shift (Type B). Briefly, the RF interaction section of the TWT consists of a section of constant-pitch helix from the signal input point to a sever, followed by another section of helix with the same constant pitch from the sever to the beginning point of the DVT helix. The DVT portion of the helix then carries the RF signal to the *output* port of the TWT. The DVT decreases the pitch in the output circuit of the TWT, slowing the circuit wave. Properly designed, this "tapering" results in better synchronization between the circuit wave and electron bunches than can be realized with a constant helix pitch. A summary of objective characteristics for both Type A and Type B WJ-3716 TWT's appears in Table I.

The constant pitch sections of the helix for the Type A WJ-3618 TWT, designed for maximum efficiency, are such that the Pierce velocity parameter, b, (ref's 4 and 5) is 0.75. This design point is indicated in figure 1, which displays the Pierce small signal factor as a function of the velocity parameter for the WJ-3618 TWT. In the output section of the helix, where the signal strength rapidly increases, the helix pitch is continuously tapered in the manner prescribed by Kosmahl and Peterson (ref. 1) to maintain the effective value of b near 0.75. The pitch distribution for this DVT design is shown in figure 2. In this configuration, the number of turns per inch of the helix increases from about 65.3 to 74.1 over the length of the output section. The predicted increase in RF efficiency resulting from the use of the DVT relative to that of a constant pitch helix circuit is shown in figure 3 as a function of input power.

For the WJ-3716 TWT Type B, designed for minimum distortion and phase shift, the constant-pitch sections of the helix are such that the Pierce velocity parameter, b, is -0.5, well into the region where small signal theory predicts relatively small phase lag. This design point is indicated on the small signal gain against velocity parameter relationship curve shown in figure 1. The DVT for this TWT is not designed to maintain the input helix value of the b parameter, but instead adjusts b toward the value for optimum efficiency. The intent of this procedure is to maintain excellent signal quality while still achieving high efficiency. The Type B DVT pitch distribution is shown in figure 2, where the helix tapers from about 60.5 to 76.0 turns per inch over the output length. The predicted RF efficiency characteristics for the Type B DVT design, shown as a function of input power in figure 3, display an impressive increase over those of the same TWT with a helix of constant pitch.

All the specifications of the WJ-3618 TWT, withthe exceptions of helix pitch and length, were used in the DVT designs for the WJ-3716 TWT described here. A large-signal, two-dimensional computer program developed by Detweiler (ref. 6) was employed to design the DVT's and refocusing sections (ref. 2) used to condition the spent electron beam for optimum input to the MDC's.

Significant differences between the spent beam conditions of the Type A and B TWT's required the design of a different four-stage MDC for each. Further, the difference in spent beam exit conditions from the two TWT types resulted in separate refocusing section designs as well. The MDC designs were performed with the use of a computer program developed by Herrmannsfeldt (ref. 7) and also included the consideration of the effect of the secondary electron emission characteristics of the collector electrode surfaces (ref. 8). The design procedure predicts the electron trajectories and electric field potentials within the cylindrically symmetrical boundaries of the MDC envelope. Input information to the calculation procedure includes MDC electrode geometry, positions and velocities of the entering electrons, and the potentials applied to the individual electrodes. Various electrode designs, spacings, and potential distributions starting with experience-dictated arrangements were interatively evaluated until the maximum predicted values of collector efficiency were attained, coupled with minimum electron back streaming. A computer graphic representation of the MDC electrode configuration and electron trajectories for the MDC for the Type A WJ-3716 TWT is shown in figure 4 (a). The physical design for that MDC is shown in figure 4 (b). The photograph of an early model of a Type A TWT presented in figure 5 illustrates the general size and configuration of the TWT's being developed in this program.

The MDC's used in this program will employ electrodes having surfaces with low secondary electron emission characteristics. As described elsewhere in this paper, three dimensionally-identical MDC's will be fabricated for each of the two TWT types. One each of these MDC's will have simply-machined high-purity isotropic graphite electrodes, and another will have ion-textured electrodes of the same material. Reference 3 presents a detailed description of these materials and some experimentally determined results of their performance in full-scale MDC tests. A third MDC for each TWT type will incorporate high-purity copper electrodes which will have been surface treated for secondary electron emission suppression. The specific surface treatment for these copper electrodes has not as yet been determined, but will be selected from one of three promising processes. Two of these processes, the sputter-application of highly-textured carbon (ref. 3) and the arc-discharge application of a thin coating of roughened carbon (ref. 9), have been well studied and have been demonstrated to be very effective. The third possible choice is the ion-texturing of the copper surface itself by means of a method currently being developed.

## EXPERIMENTAL RESULTS AND CONCLUDING REMARKS

The first of the Type A and B TWT's mated with single stage undepressed collectors have been fabricated at the Watkins-Johnson company. In hot testing, they have shown good agreement between predicted and measured RF efficiencies. Further, the circuits have displayed as high as 30 percent improvement in RF efficiency over conventional constant-pitch helix designs. Table II presents some selected test results for the first of each type TWT operating at 100 percent duty cycle at 8.4 GHz. While the experimentally-determined beam transmission efficiency is less than desired at present, the measured phase shift characteristics must be regarded as quite encouraging at this stage in the program. Further, the measured values of beam efficiency for both Type A and B TWT's are considered to be quite satisfactory at this point. With the scheduled addition of the high-efficiency MDC's to the tubes, reaching or exceeding the program goal of 55 percent overall efficiency is considered to have a very high probability of success for both TWT types.

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TABLE I. - OBJECTIVE CHARACTERISTICS OF WJ-3716 TWT TYPES A AND B

| | |
|---|---|
| Frequency, GHz | 8.4 to 8.43 |
| Min. sat. RF output power in band, W | 20 |
| Overall efficiency, percent | 55 |
| Saturated gain (Type A), dB | 48 |
| Beam transmission at saturation, percent | >99 |
| Dispenser cathode type | M |
| Cathode voltage, kV | 4 or less |
| Heater power, W | 3.4 |
| Beam focusing | periodic permanent magnet |
| Refocusing system | periodic permanent magnet |
| Design lifetime, years | >10 |

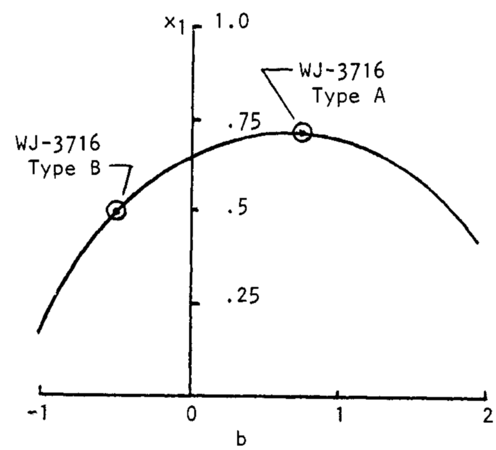



Figure 1. - Pierce small signal gain factor $x_1$ as a function of velocity factor b for the WJ-3618 TWT, showing the helix input section design points for the WJ-3716 TWT's.

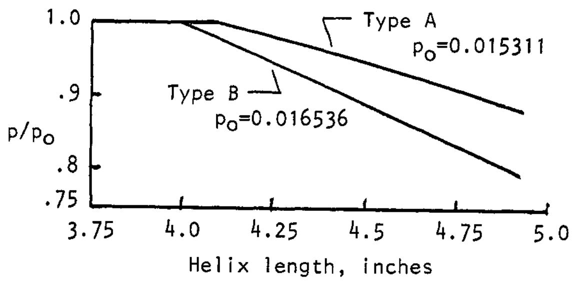



Figure 2. - DVT helix pitch distribution for WJ-3716 TWT's.

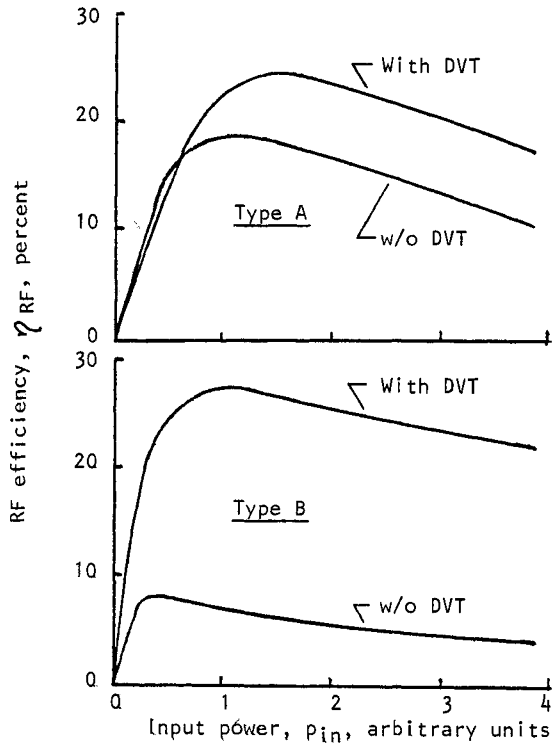
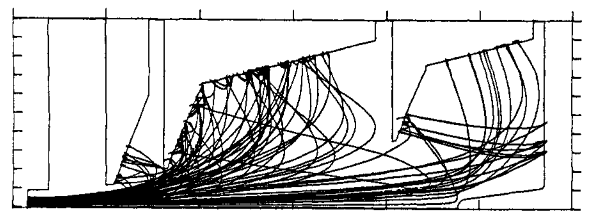
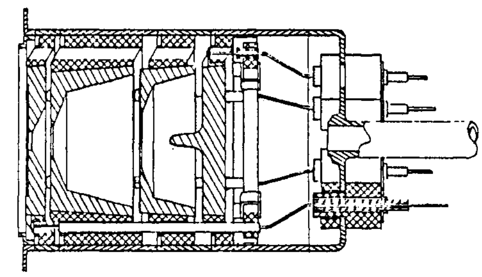



Figure 3. - Predicted RF efficiency as a function of input power for WJ-3617 TWT's with and without DVT's.



(a) Electron trajectory traces



(b) Assembly

Figure 4. - Electron trajectory characteristics and assembly configuration for MDC for Type A WJ-3716 TWT.

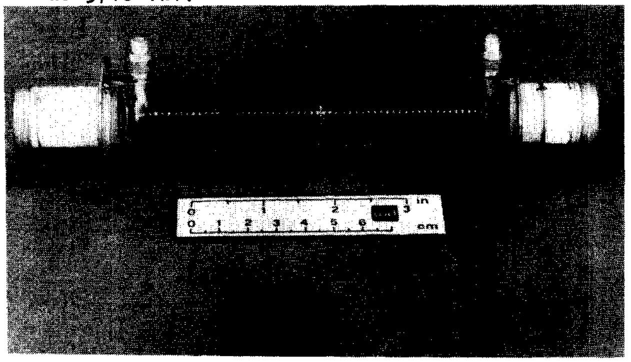


Figure 5. - Type A WJ-3716 TWT with undepressed collector (at left) prior to installation of permanent magnets in interaction and refocusing sections.

TABLE II. - SELECTED TEST RESULTS FROM FIRST WJ-3716 TWT'S AT 8.4 GHz AND 100 PERCENT DUTY CYCLE

| PARAMETER | TWT TYPE | |
|---|---|---|
| | A | B |
| Helix voltage, volts | 3150 | 3235 |
| Beam current, mA | 32 | 27.5 |
| Saturated gain, dB | 51.71 | 41.0 |
| Beam efficiency, percent | 24.4 | 25.2 |
| Saturated RF output power, $dB_m$ | 43.91 | 43.5 |
| Helix current, mA | 1.5 | 1.25 |
| Beam transmission efficiency, percent | 95.3 | 95.5 |
| Phase shift at saturation, deg/dB | 4.84 | 3.13 |

WJ-3716 TWT.

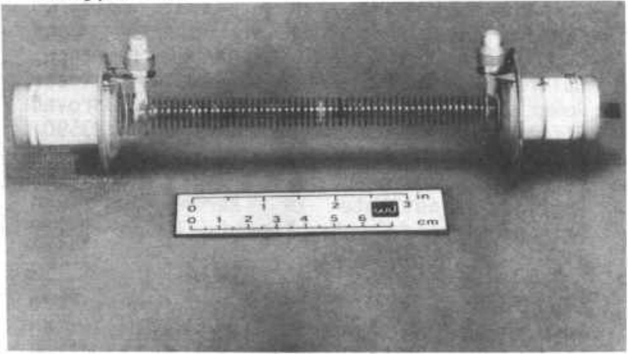



Figure 5. - Type A WJ-3716 TWT with undepressed collector (at left) prior to installation of permanent magnets in interaction and refocusing sections.

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